SM Higgs Searches at the Tevatron!

(high mass)

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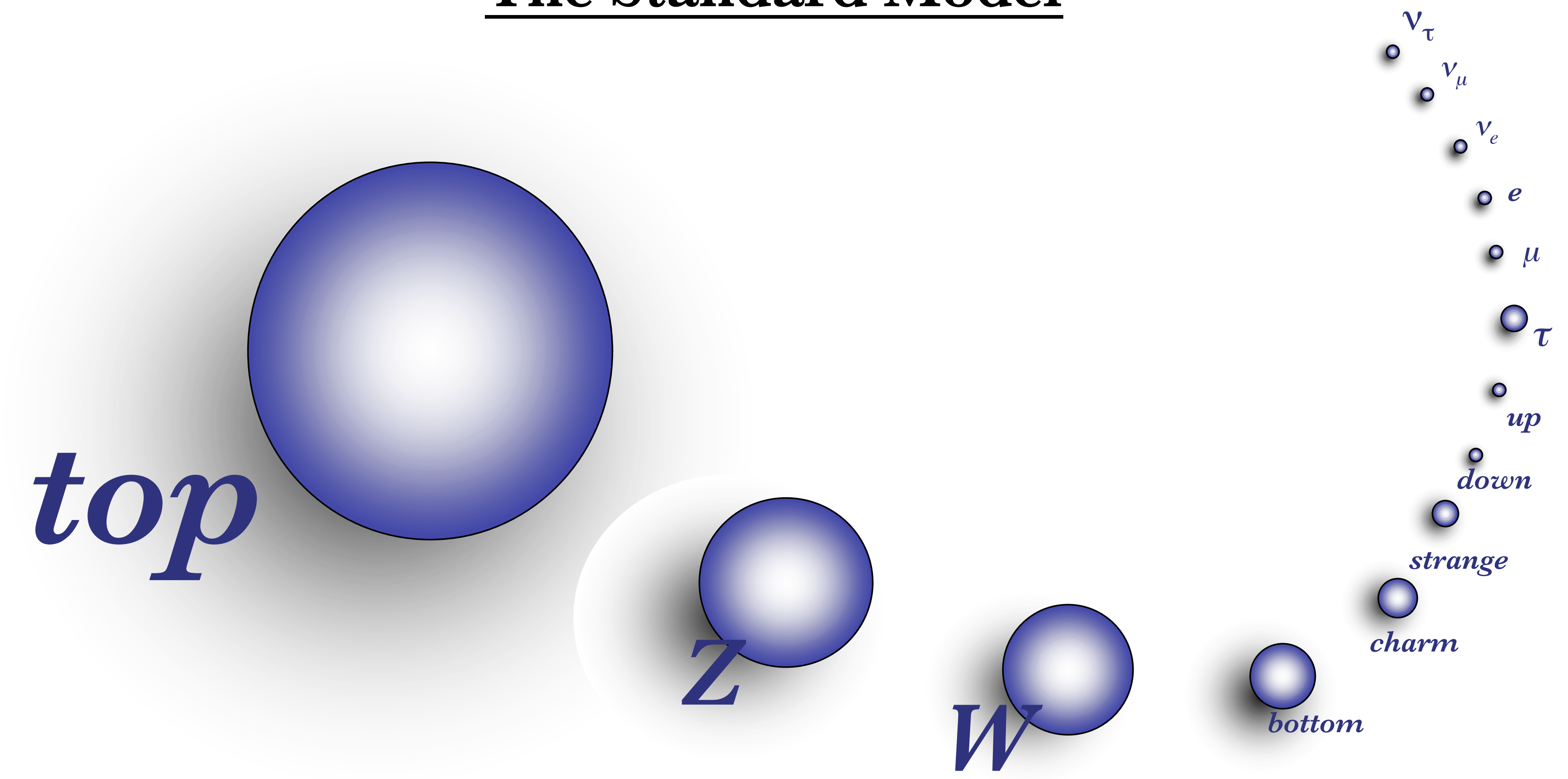
UCIrvine

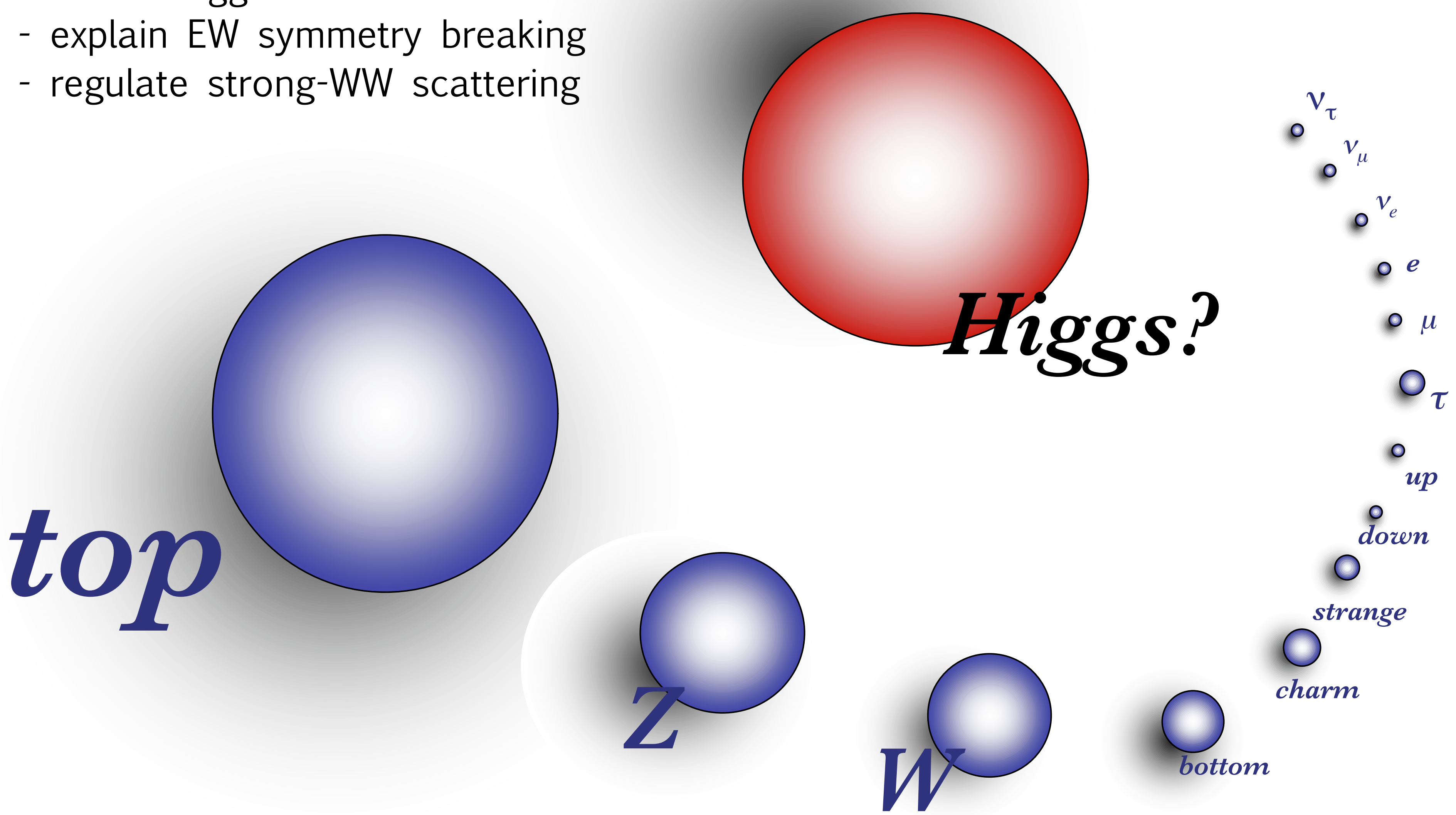
The Standard Model



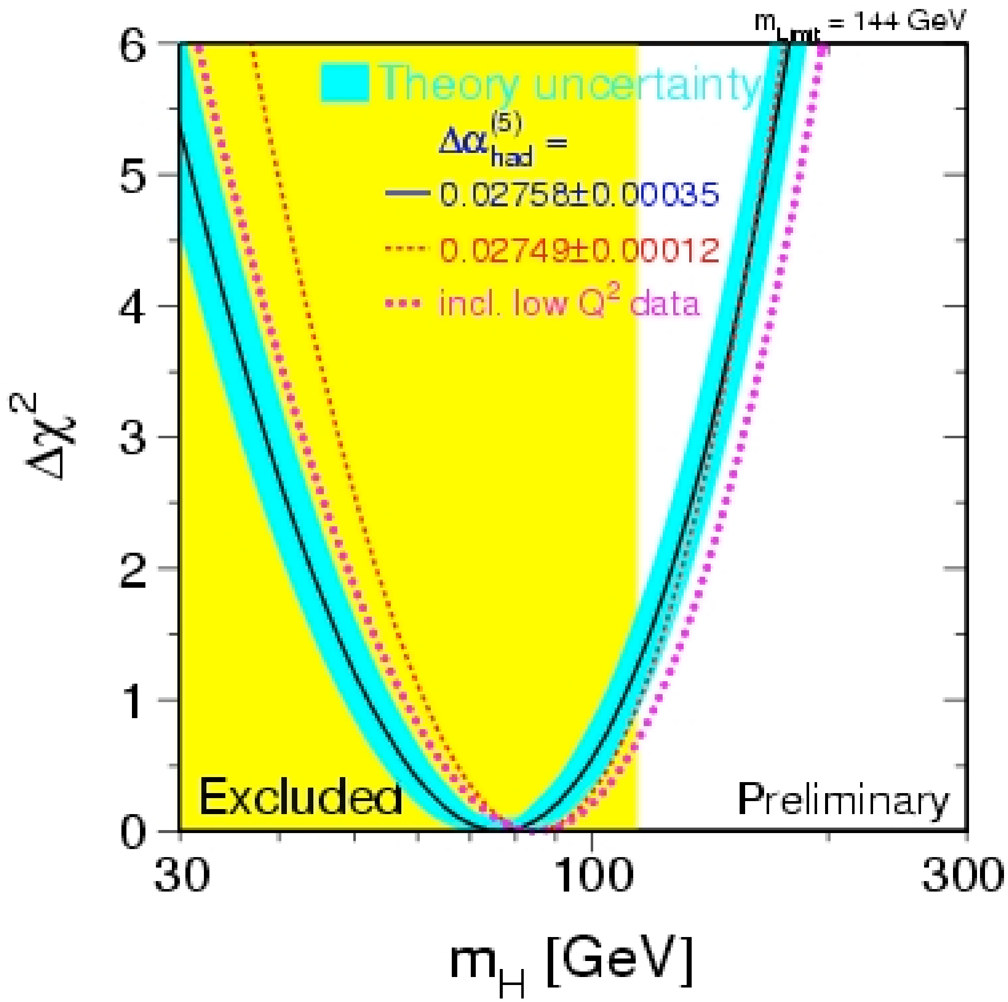
State of the Art

Standard Model needs a Higgs

- ...or a Higgs-like mechanism
- explain EW symmetry breaking
- regulate strong-WW scattering



Current limits



LEP direct Searches
m_H > 114.1 GeV

Tevatron opportunity

State of the Art?

The Standard Model

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig^2_s(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$

$$\frac{1}{2}m^2_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s^2_w-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s^2_wA_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial+m^\lambda_d)d^\lambda_j + igs_wA_\mu\left[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right] +$$

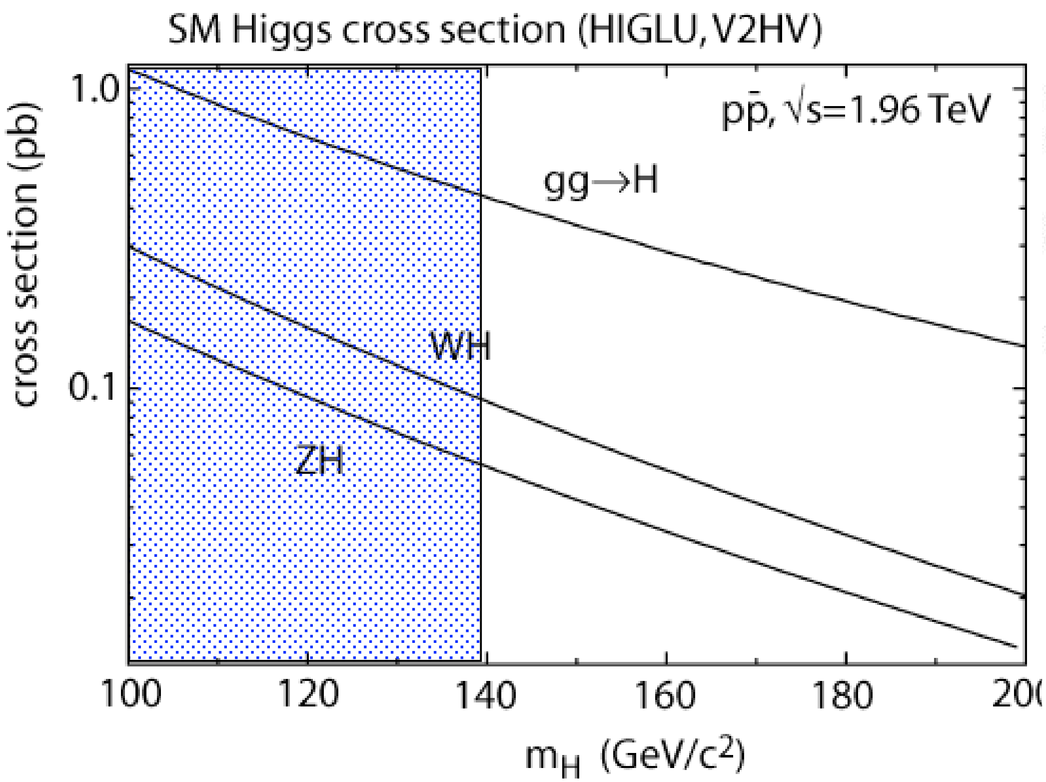
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w-1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s^2_w-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

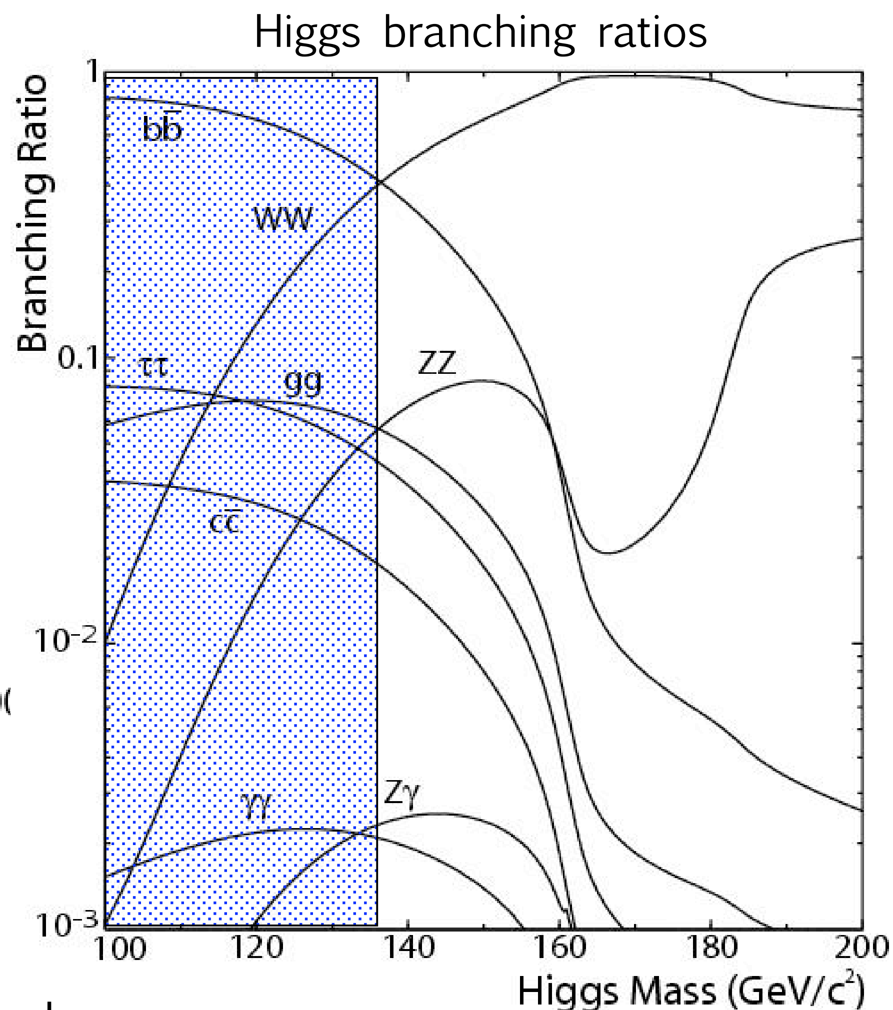
$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) -$$

$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c^2_w}\bar{X}^0X^0H] +$$

$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Higgs Production





Low mass

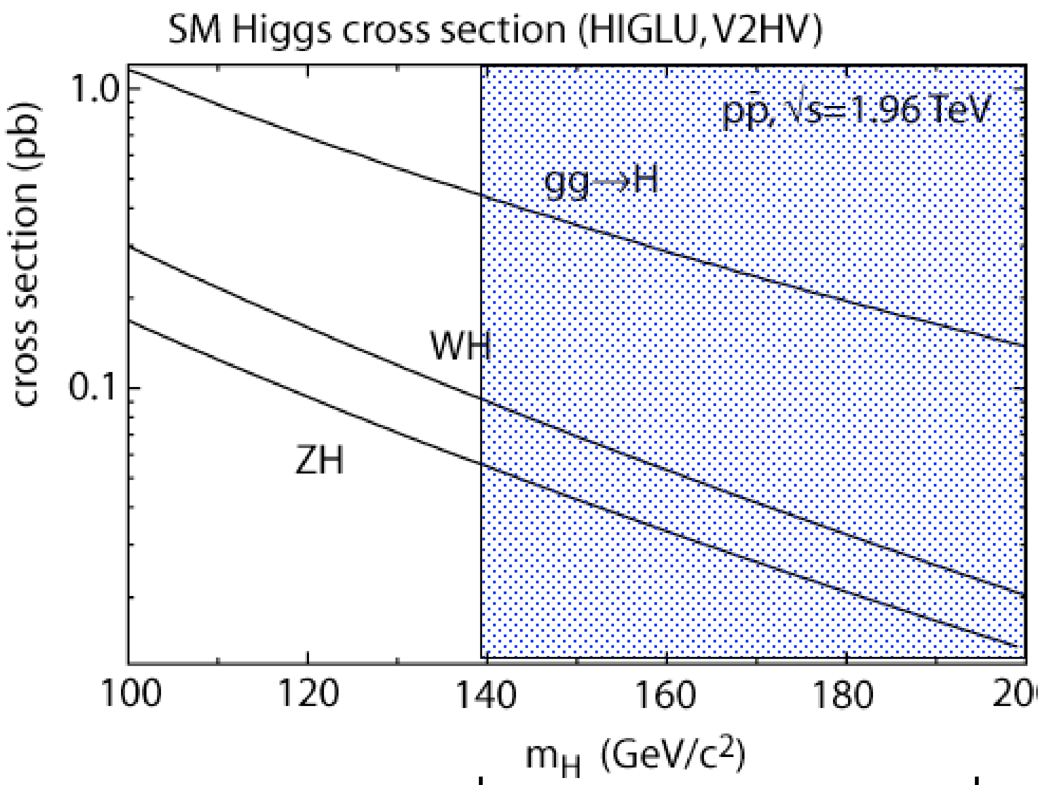
gg -> H -> bb dominates

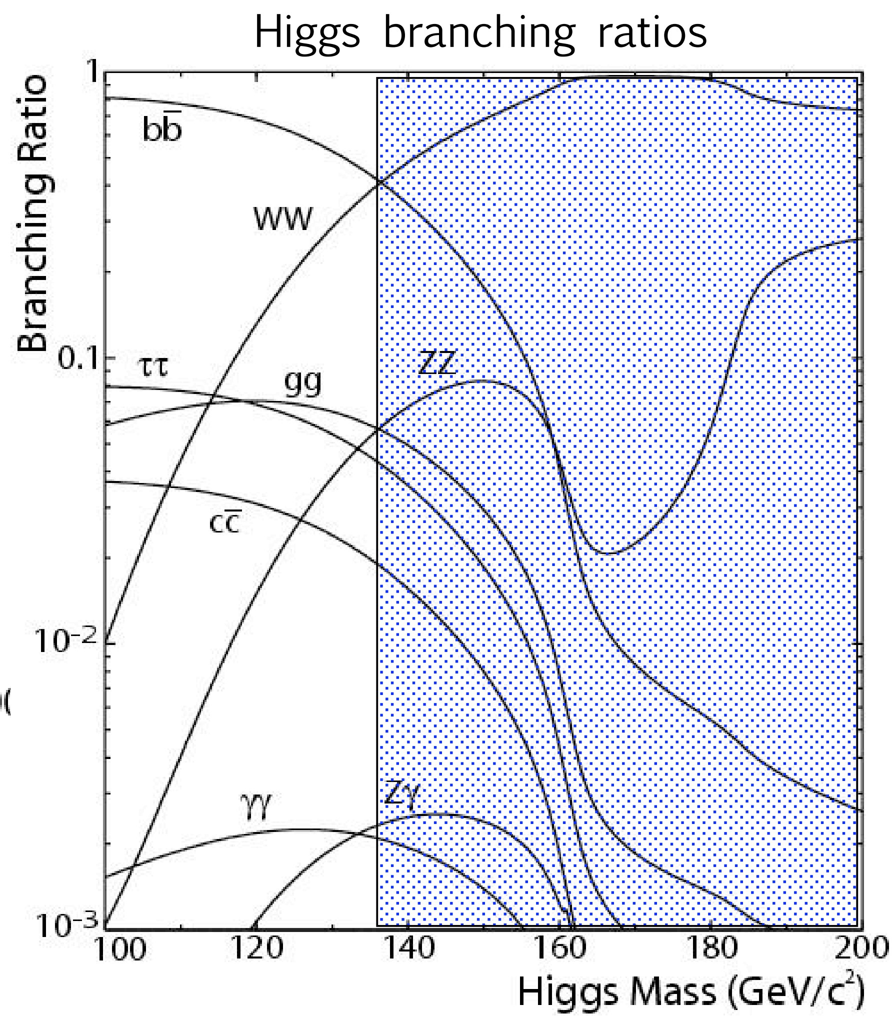
Nearly impossible to see over background

Wh, Zh channels difficult but possible

(See talk by M. Sanders)

Higgs Production





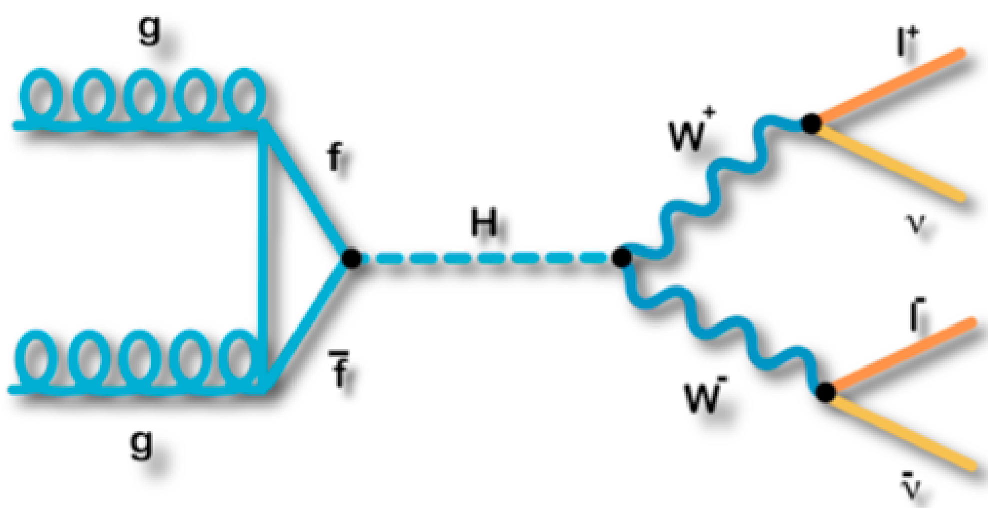
High mass

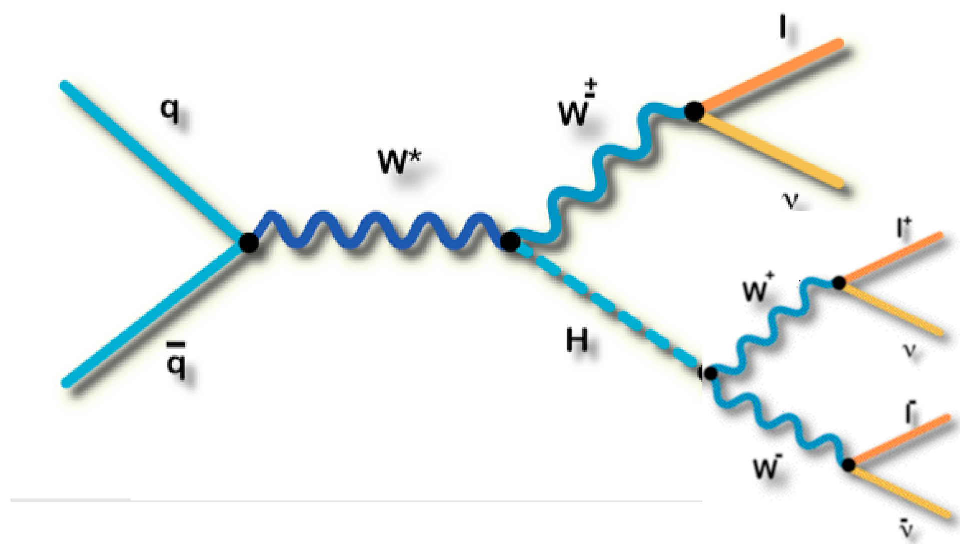
gg -> H -> WW dominates

VH -> VWW contributes

Vector boson fusion can also contribute

Analyzed SM channels (high mass)





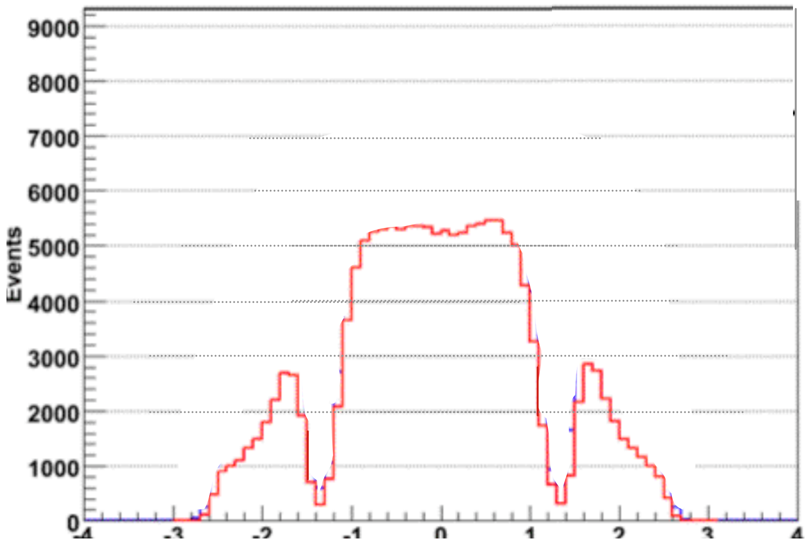
Experimental objects

Leptons (e/μ)

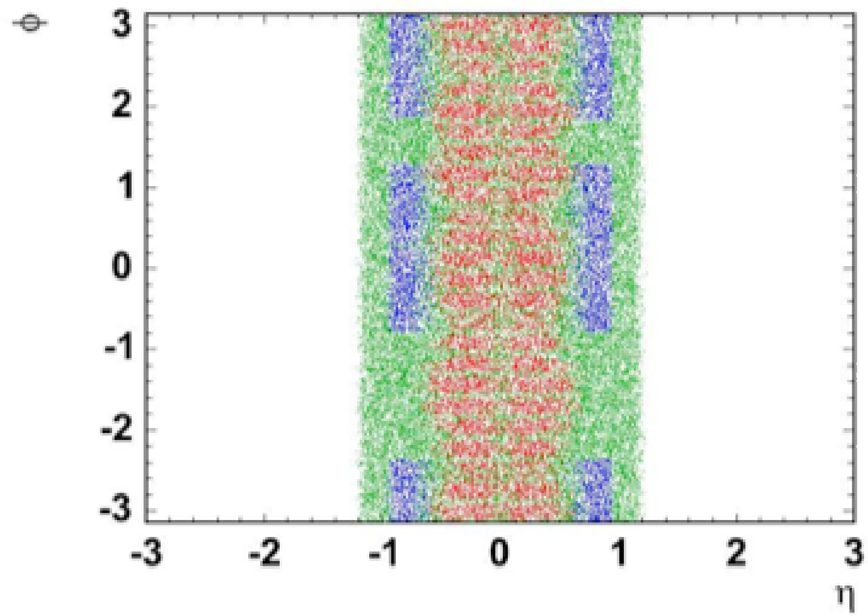
Missing Energy

Lepton acceptance

e.g. Electrons at D0



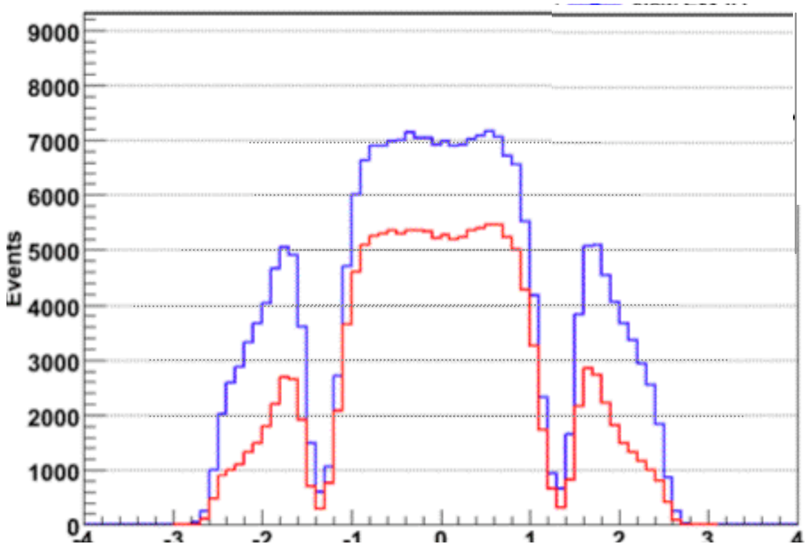
e.g. Muons at CDF



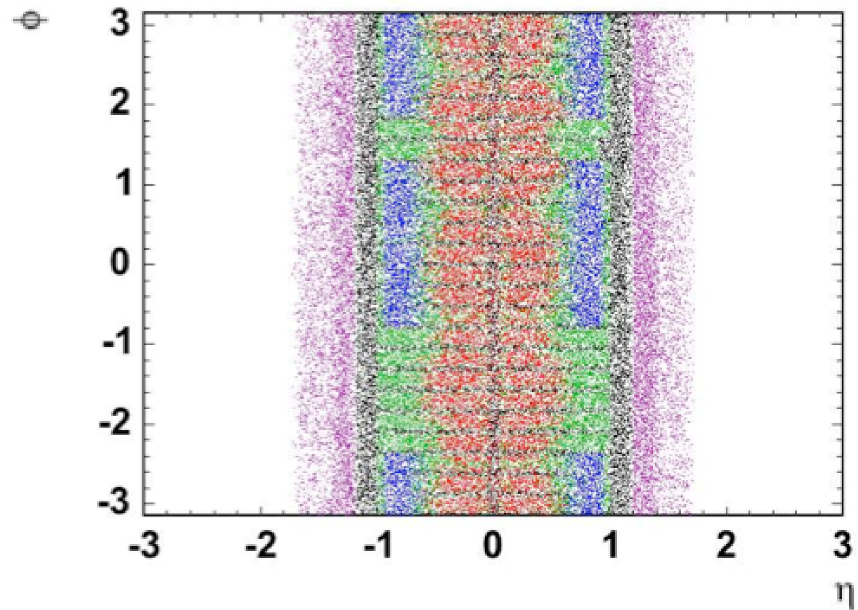
Standard lepton identification

Lepton acceptance

e.g. Electrons at D0



e.g. Muons at CDF

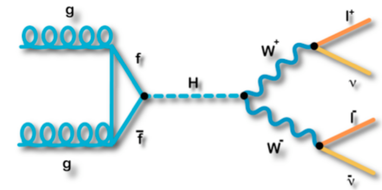


Improved lepton acceptance

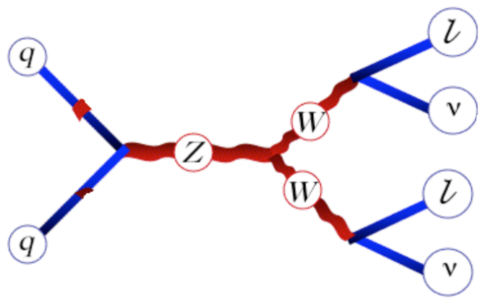
CDF: Use every track, forward MIP signals

D0: Loosened electron ID requirements using neural network

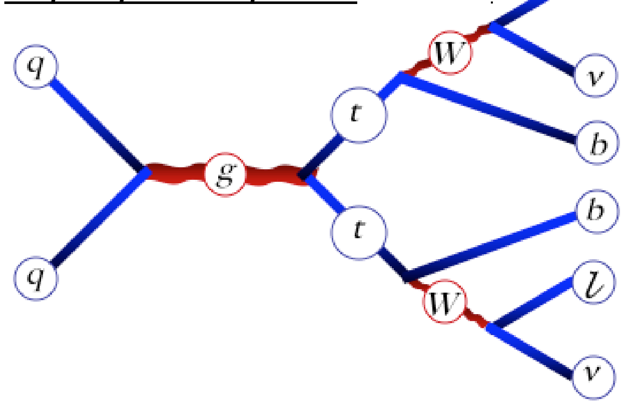
H-> WW Backgrounds



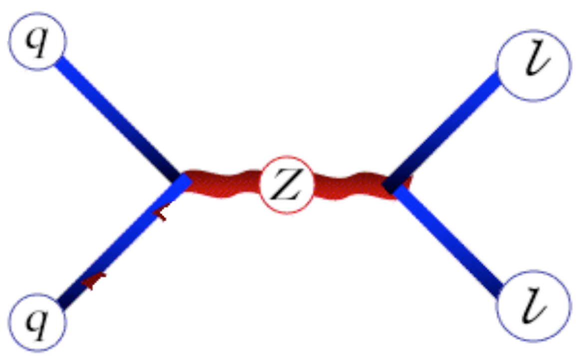
Diboson (WW/WZ/ZZ)



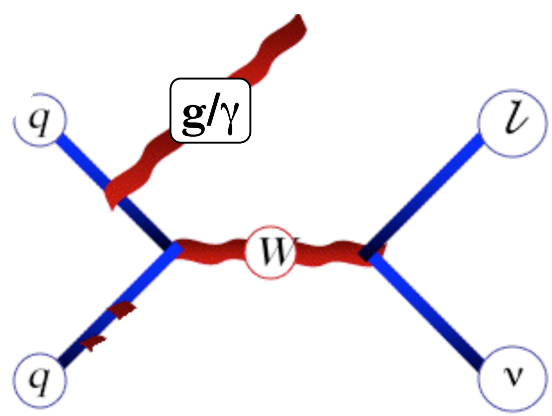
top quark pairs



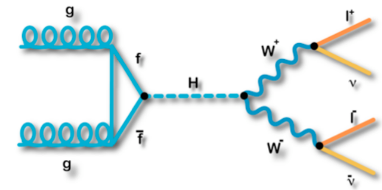
Drell-Yan

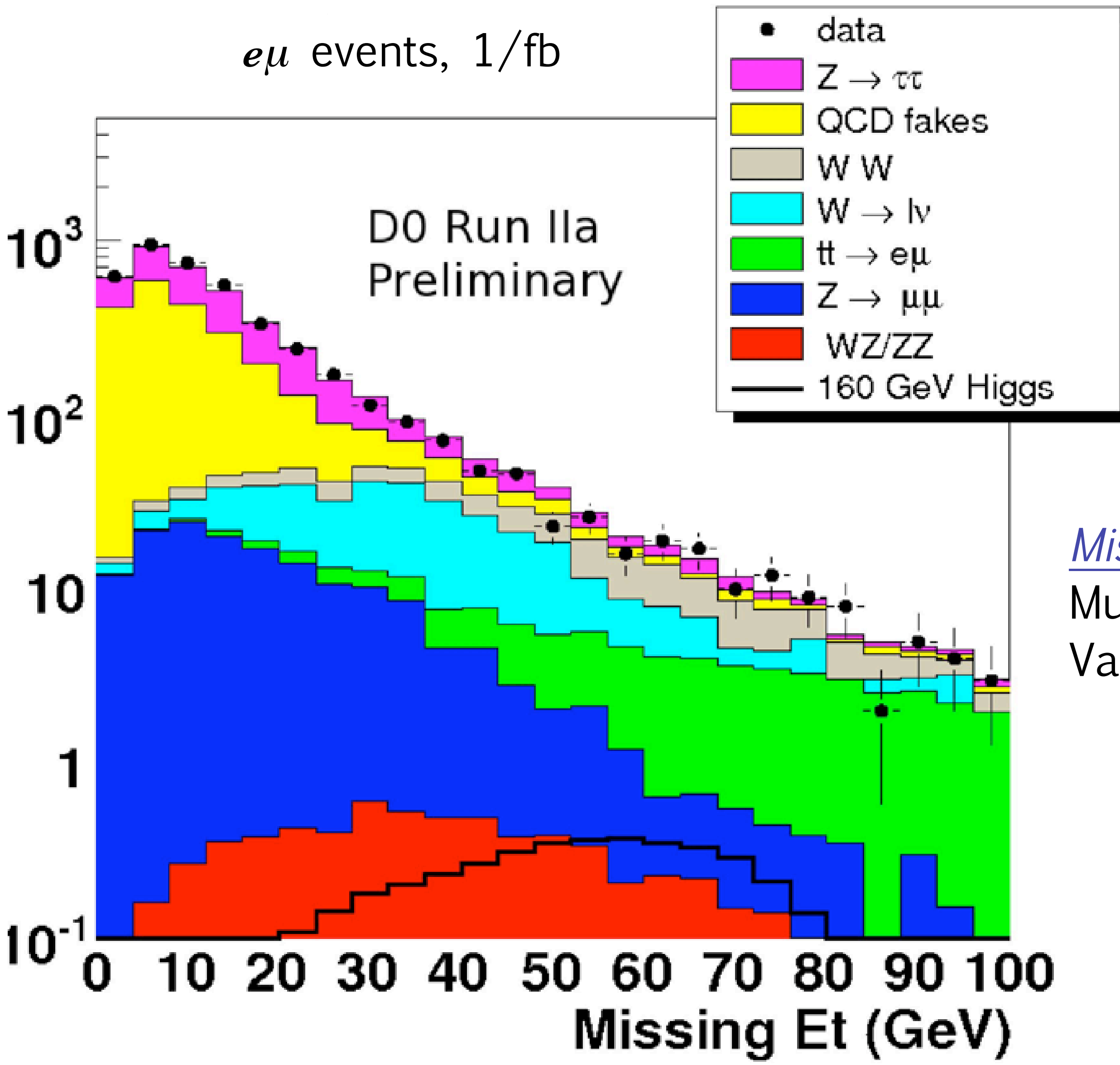


W+g/γ (fake lepton)



Missing energy



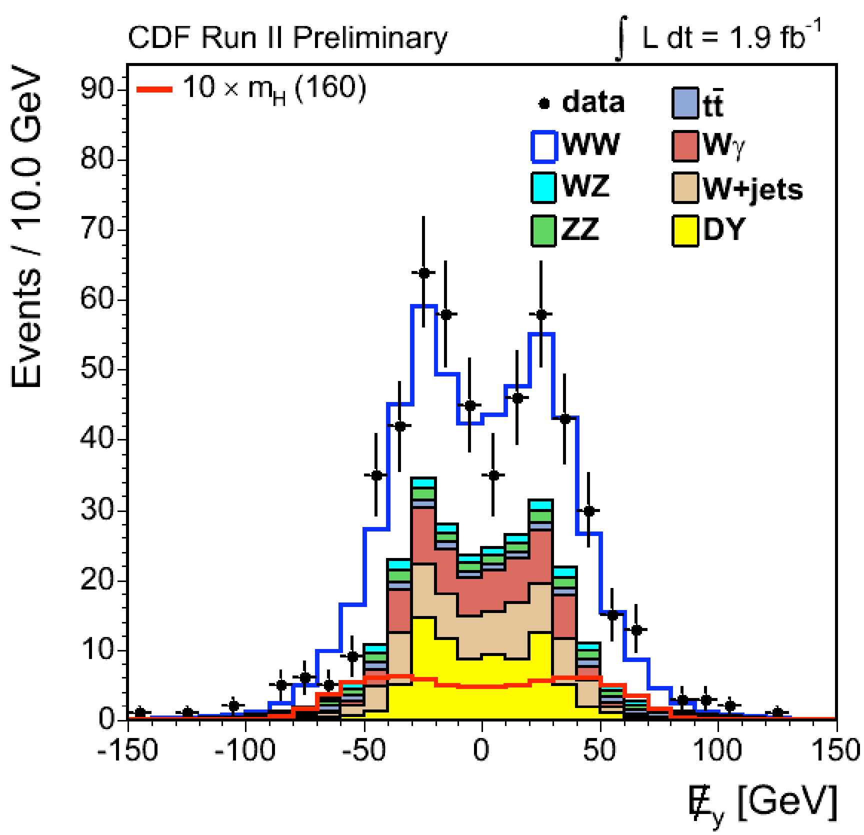


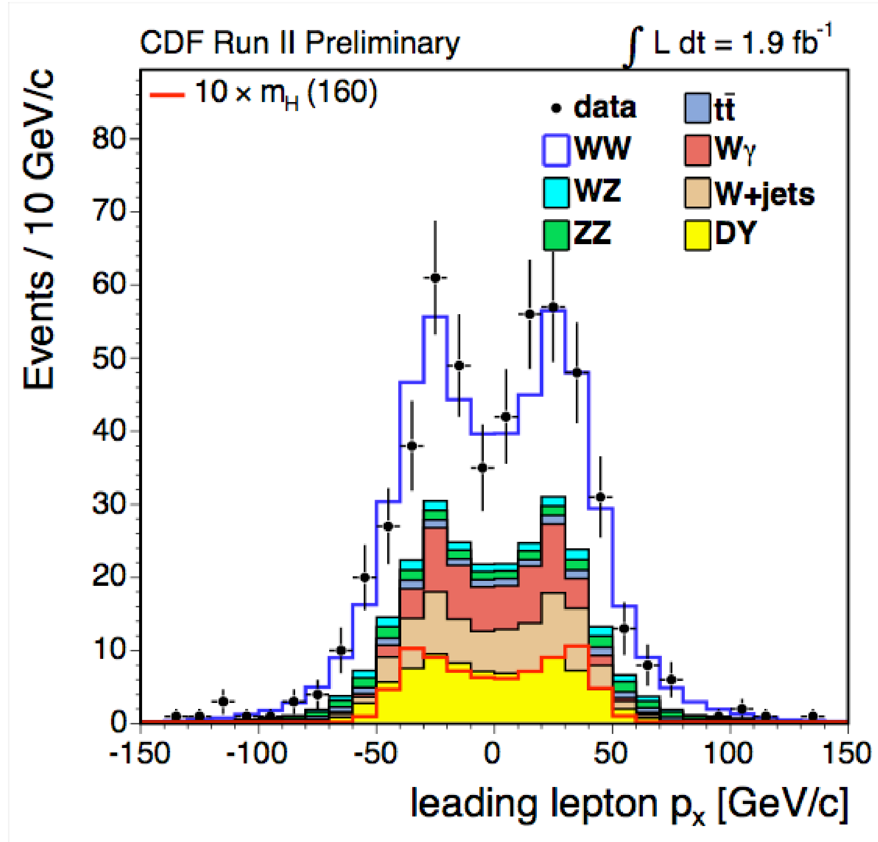
Missing energy

Must be well understood

Validated in control samples

Validation





Simulated samples are well validated by data

Sample Composition

Selection

Two leptons

Missing energy

< 2 jets

D0 eμ only (1/fb)

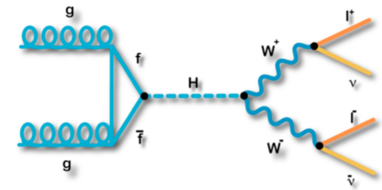
M_H (GeV)	160
$H \to W^+W^-$	1.64 ± 0.03
$Z/\gamma \to ll$	0.2 ± 0.1
Diboson (WW, WZ)	13.2 ± 0.1
$t\bar{t}$	1.25 ± 0.1
W+jet/γ	7.5 ± 1.9
Multi-jet	2.1 ± 0.2
Background sum	24.2 ± 2.0
Data	20

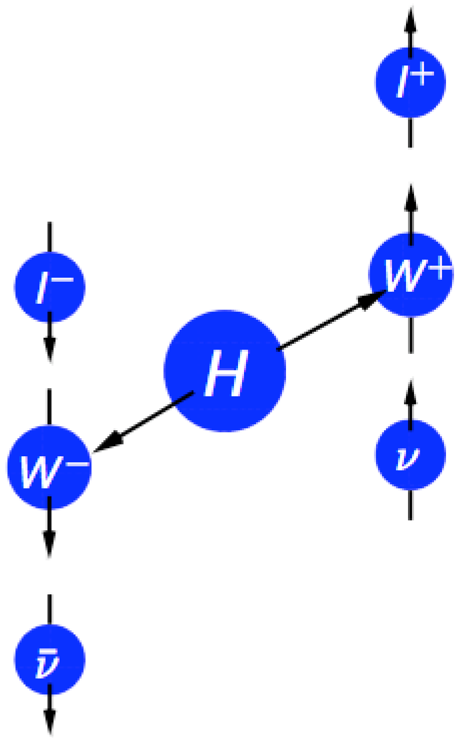
CDF Run II Preliminary $\int \mathcal{L} = 1.9 fb^{-1}$

$M_H = 160$ GeV/c^2

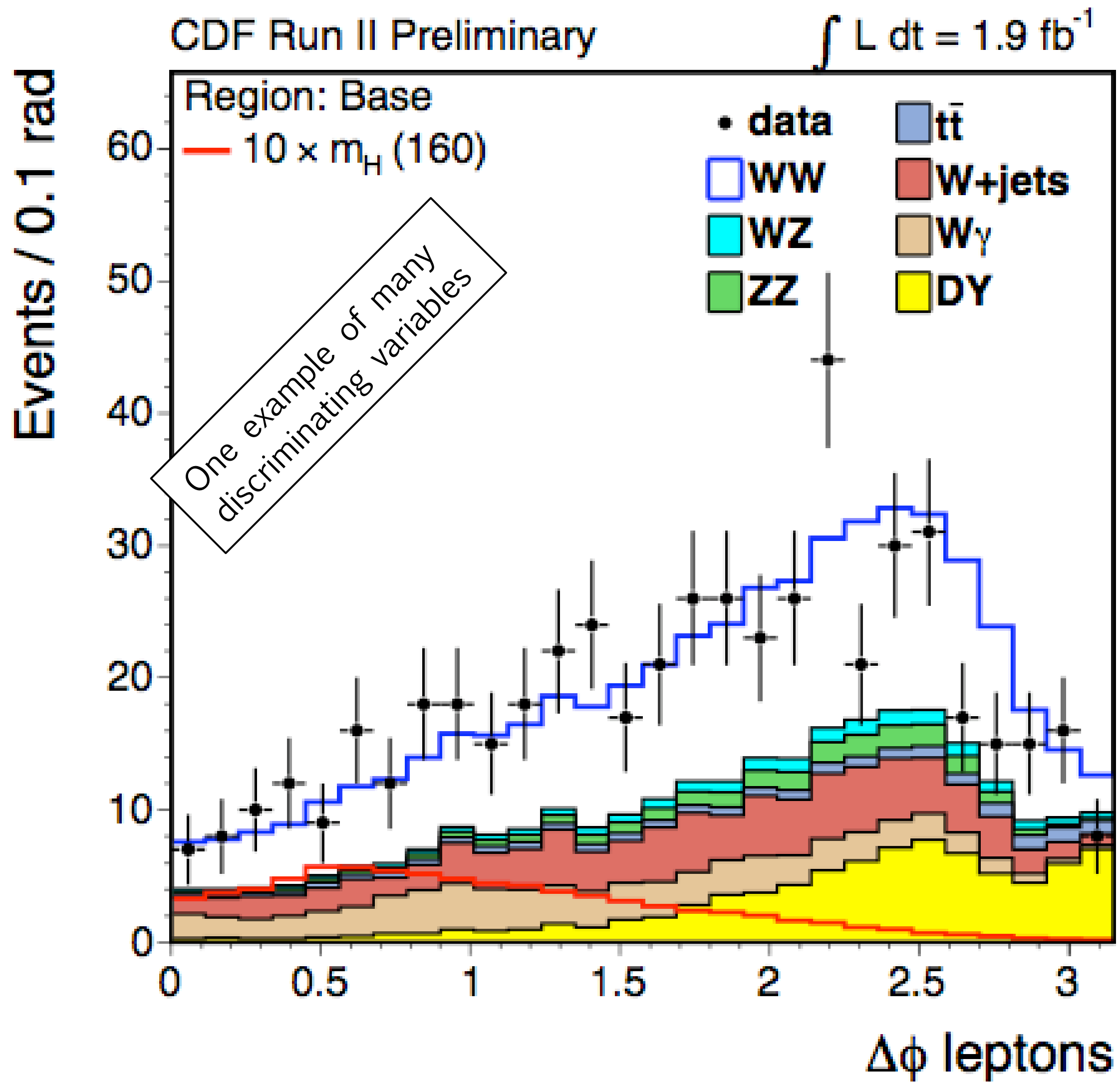
$H \to WW$	7.7	$\pm$	0.8
WW	249.1	$\pm$	29.6
WZ	16.8	$\pm$	2.5
ZZ	14.8	$\pm$	2.2
$t\bar{t}$	17.2	$\pm$	3.2
DY	81.8	$\pm$	17.9
$W\gamma$	58.4	$\pm$	15.0
$W + jets$	68.2	$\pm$	15.3
Total BG	**506**	$\pm$	**41**
Data		**521**	

Kinematic selection & separation

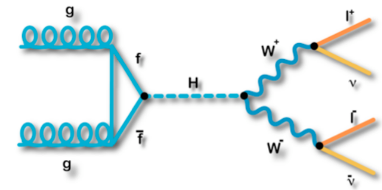


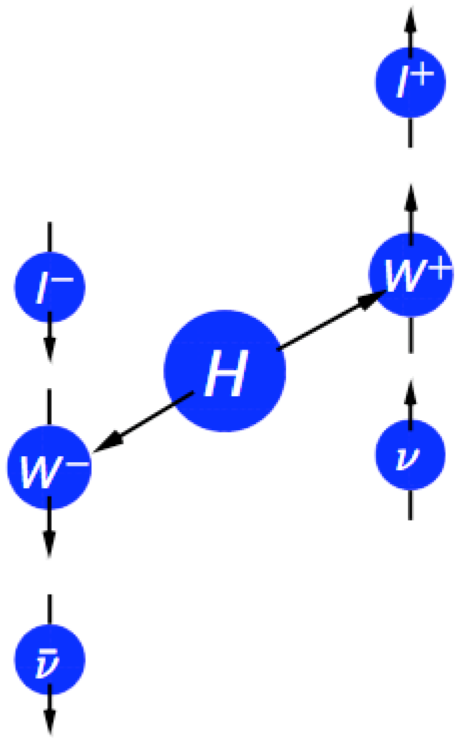


scalar decay
W spins correlated
Leptons more collinear



Kinematic selection & separation





Separation

CDF calculates probability, integrating over matrix element:

$$P(\vec{x}_{obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{obs}, \vec{y}) d\vec{y}$$

Theory at leading order

$\sigma_{th}(\vec{y})$	leading order calculation of the cross-section
$\vec{y}$	true lepton four-vector (include neutrinos)

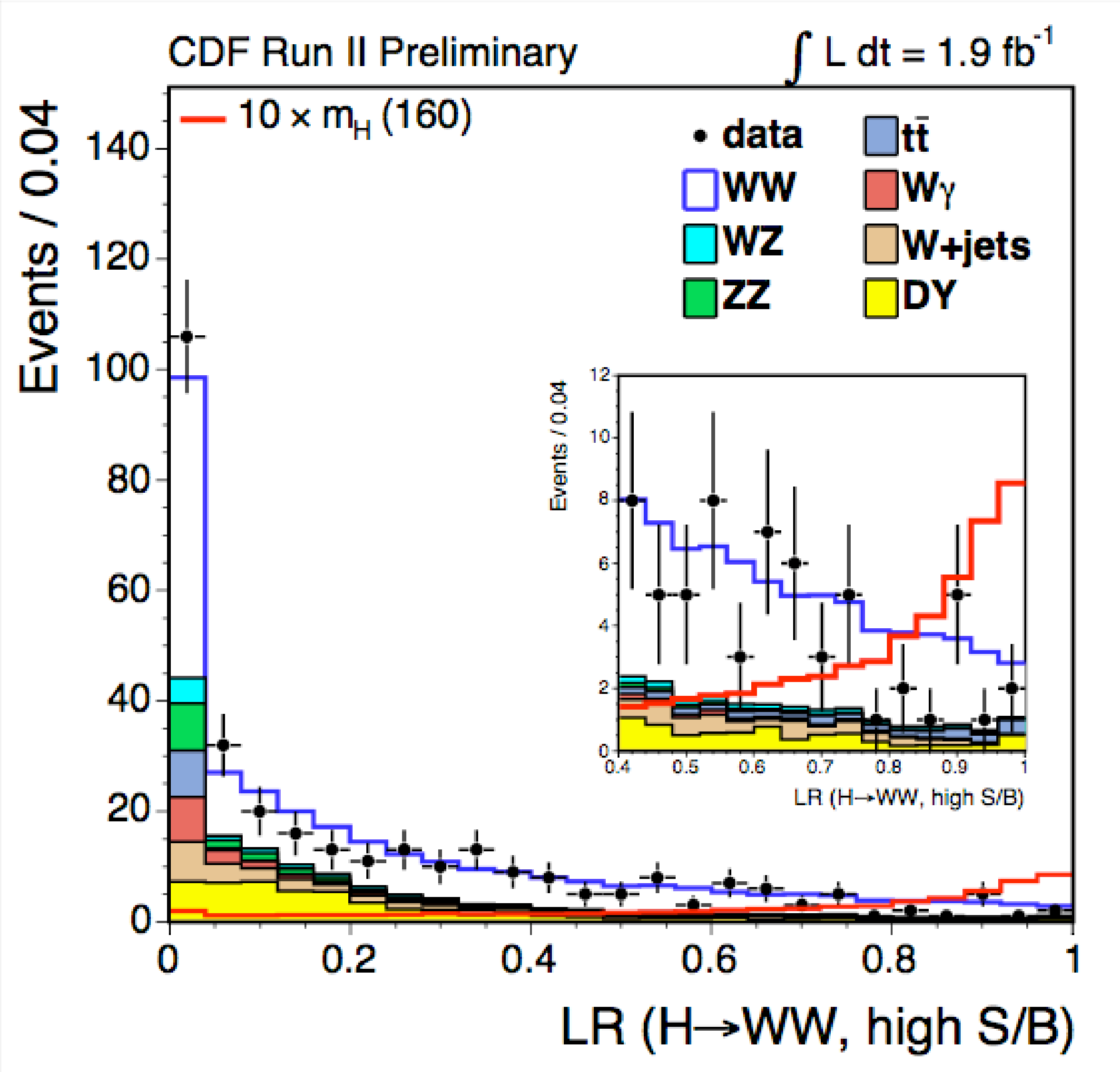
What we measure

$\vec{x}_{obs}$	observed "leptons" and $\vec{\not{E}}_T$

Detector Effects

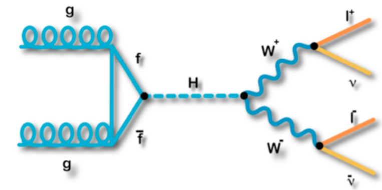
$\epsilon(\vec{y})$	total event efficiency $\times$ acceptance
$G(\vec{x}_{obs}, \vec{y})$	resolution effects

Validation



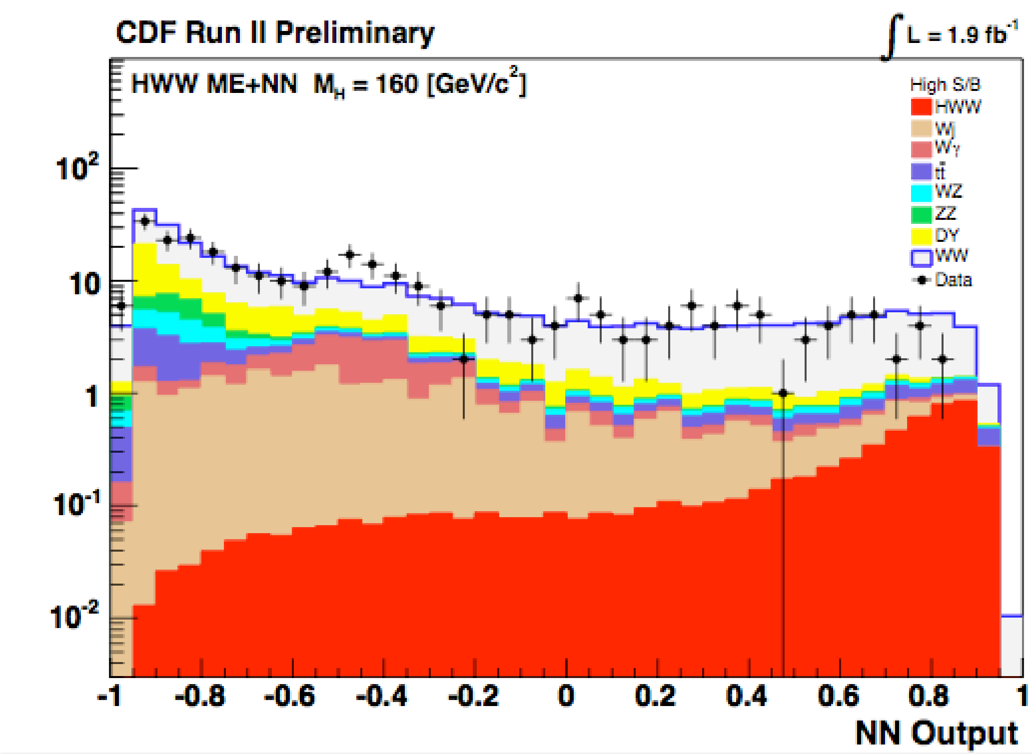
$$LR = \frac{P_{signal}}{P_{signal} + P_{bg}}$$

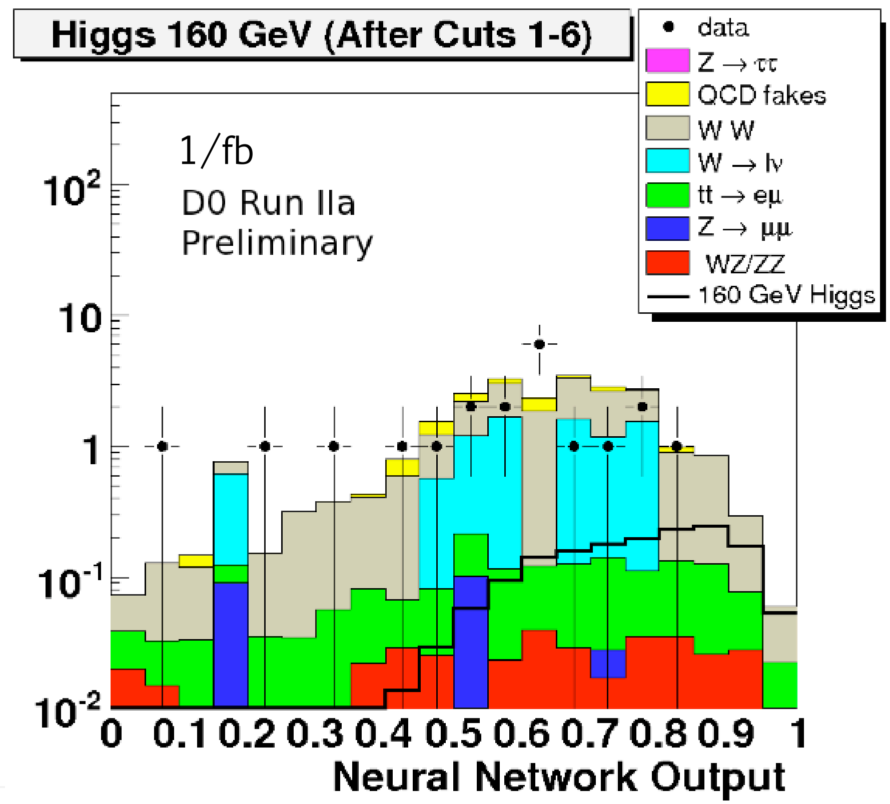
Results



Neural network

- use many discriminating variables ($\Delta\phi$, etc)
- CDF adds LRs from probability calculations
- combines all discrimination into single dimension





Systematics

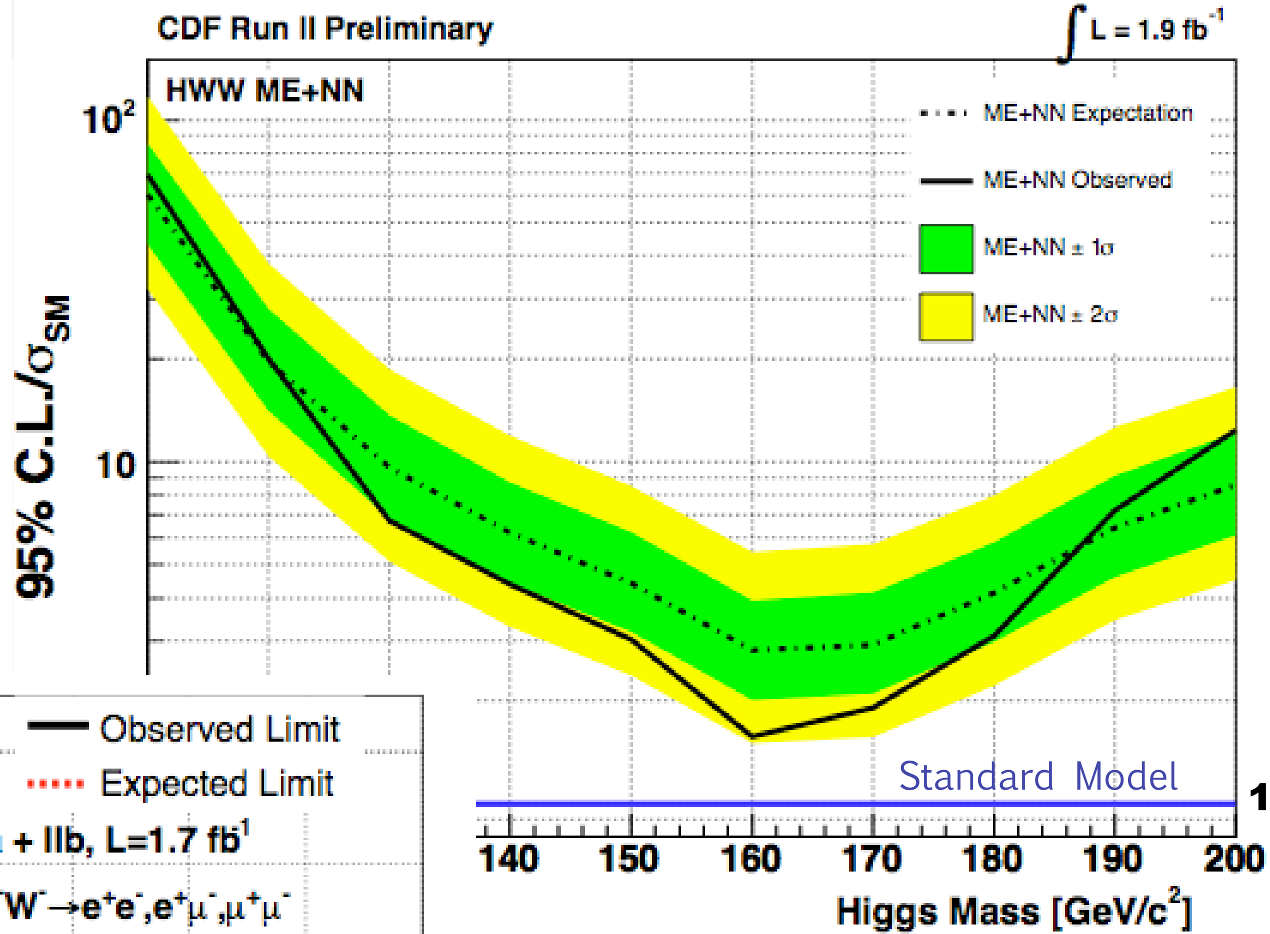
CDF Run II Preliminary $\int \mathcal{L} = 1.9 fb^{-1}$

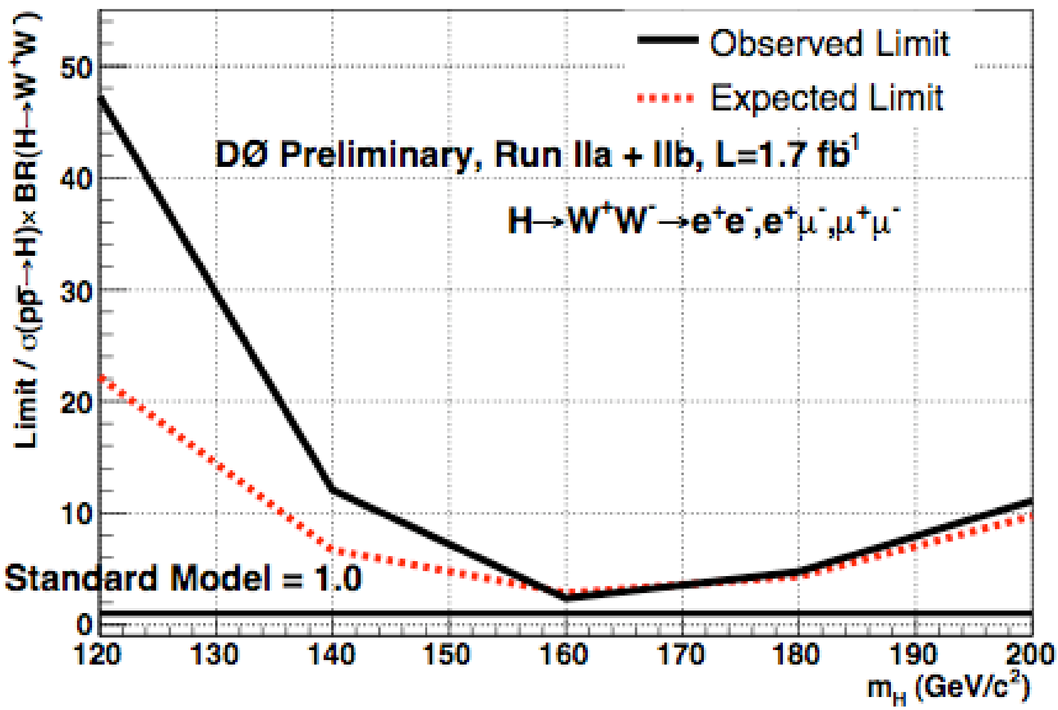
	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Higgs
$\not\!\!E_T$ Modeling	1.0	1.0	1.0	1.0	20.0	1.0	-	1.0
Conversions	-	-	-	-	-	20.0	-	-
NLO Acceptance	5.5	10.0	10.0	10.0	5.0	10.0	-	10.0
Cross-section	10.0	10.0	10.0	15.0	5.0	10.0	-	-
PDF Uncertainty	1.9	2.7	2.7	2.1	4.1	2.2	-	2.2
LepId $\pm 1\sigma$	1.5	1.4	1.3	1.5	1.5	1.2	-	1.5
Trigger Eff	2.1	2.1	2.1	2.0	3.4	7.0	-	3.3
Total	11.9	14.7	14.6	18.4	21.9	25.6	22.5	10.9

Results

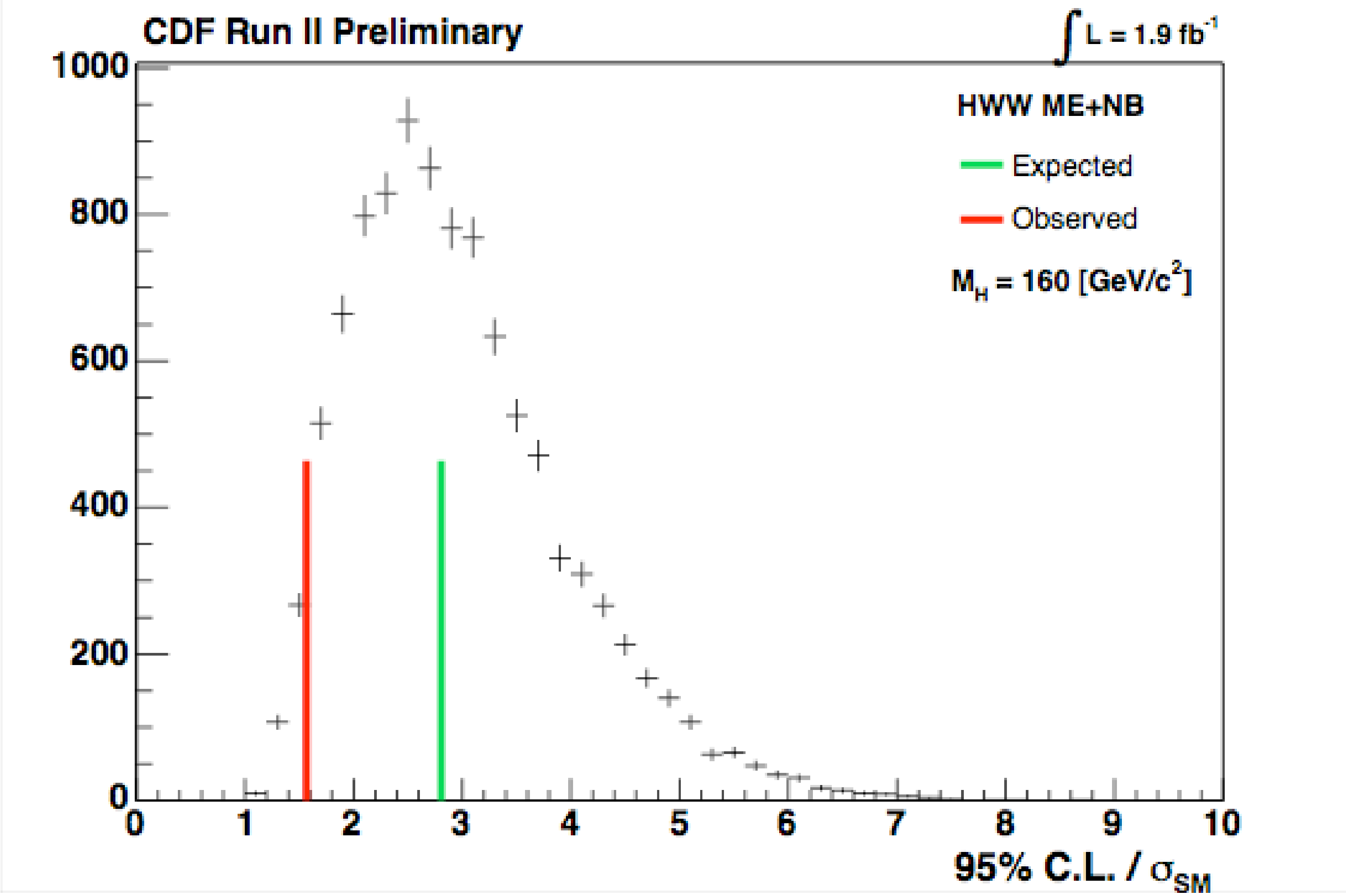
Limits are set using CL_s method

M_h=160	exp.	obs.
CDF	2.8	1.6
D0	2.8	2.4



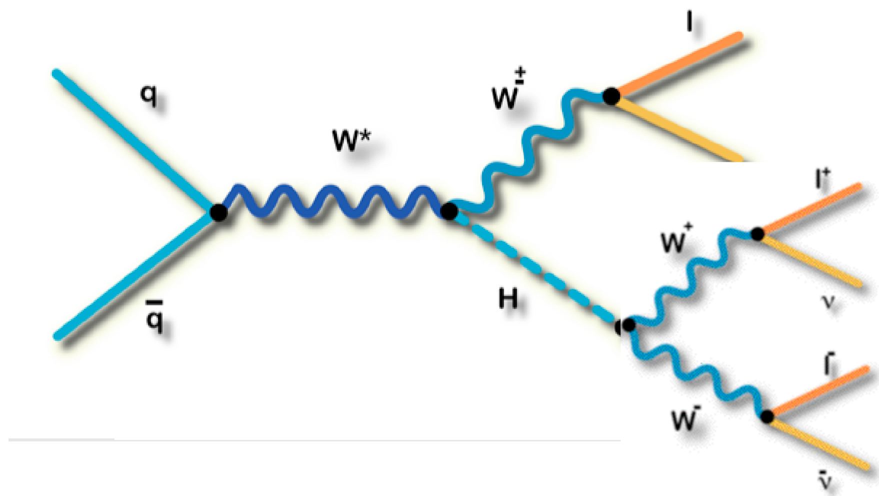


Luckiness



CDF Run II Preliminary
$\int L = 1.9\ fb^{-1}$
HWW ME+NB
Expected
Observed
$M_H = 160\ [GeV/c^2]$
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
95% C.L. / σ_{SM}

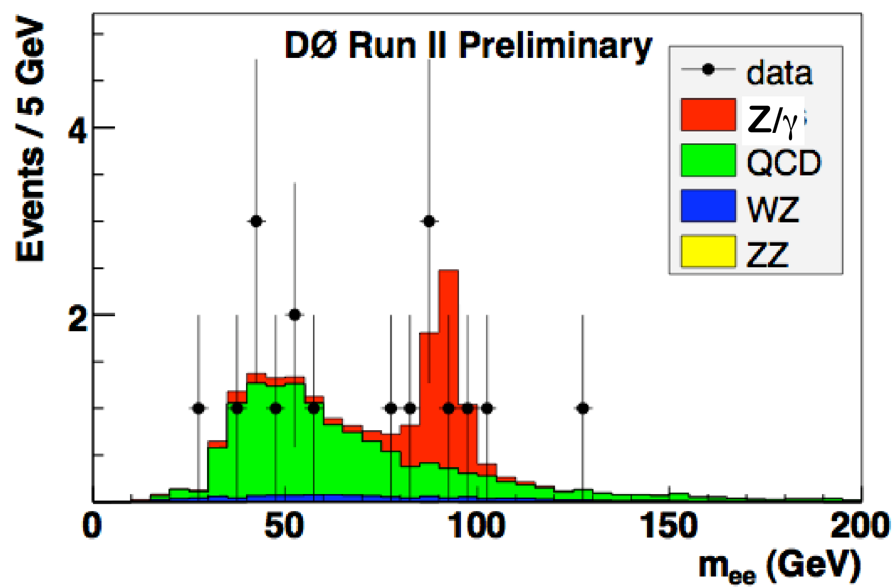
WH -> WWW



Selection
2 *like-signed* leptons

D0, 1/fb

	ee	*eμ*	*μμ*
Diboson	*1.4*	*2.6*	*1.4*
Z/γ	*11.9*		*0.8*
QCD	*7.4*	*15.4*	*2.8*
Total	20.6	18.0	5.0
Wh(160)	*0.1*	*0.2*	*0.1*
Data	19	15	5



WH -> WWW

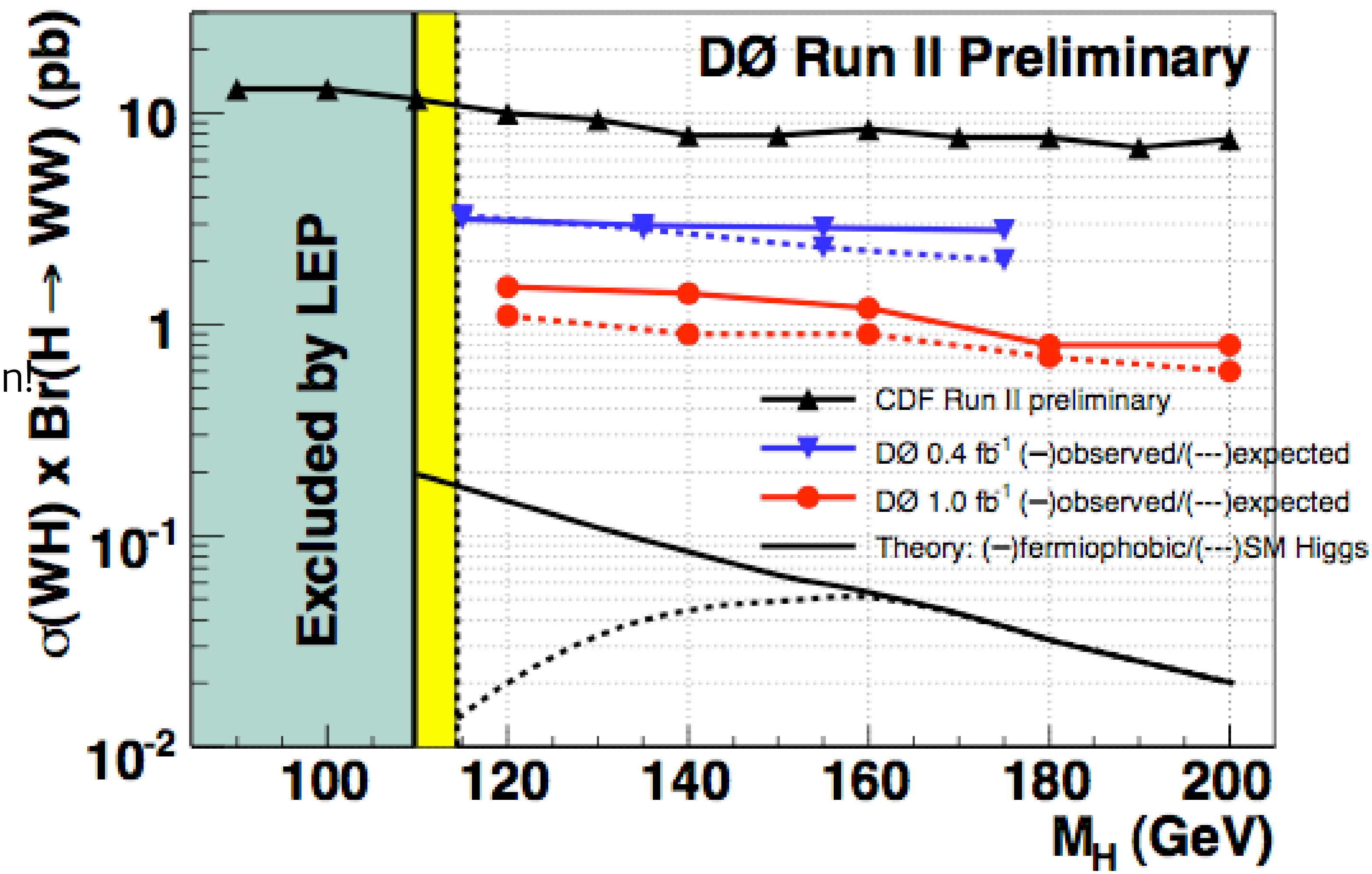
Limits

D0: 1/fb

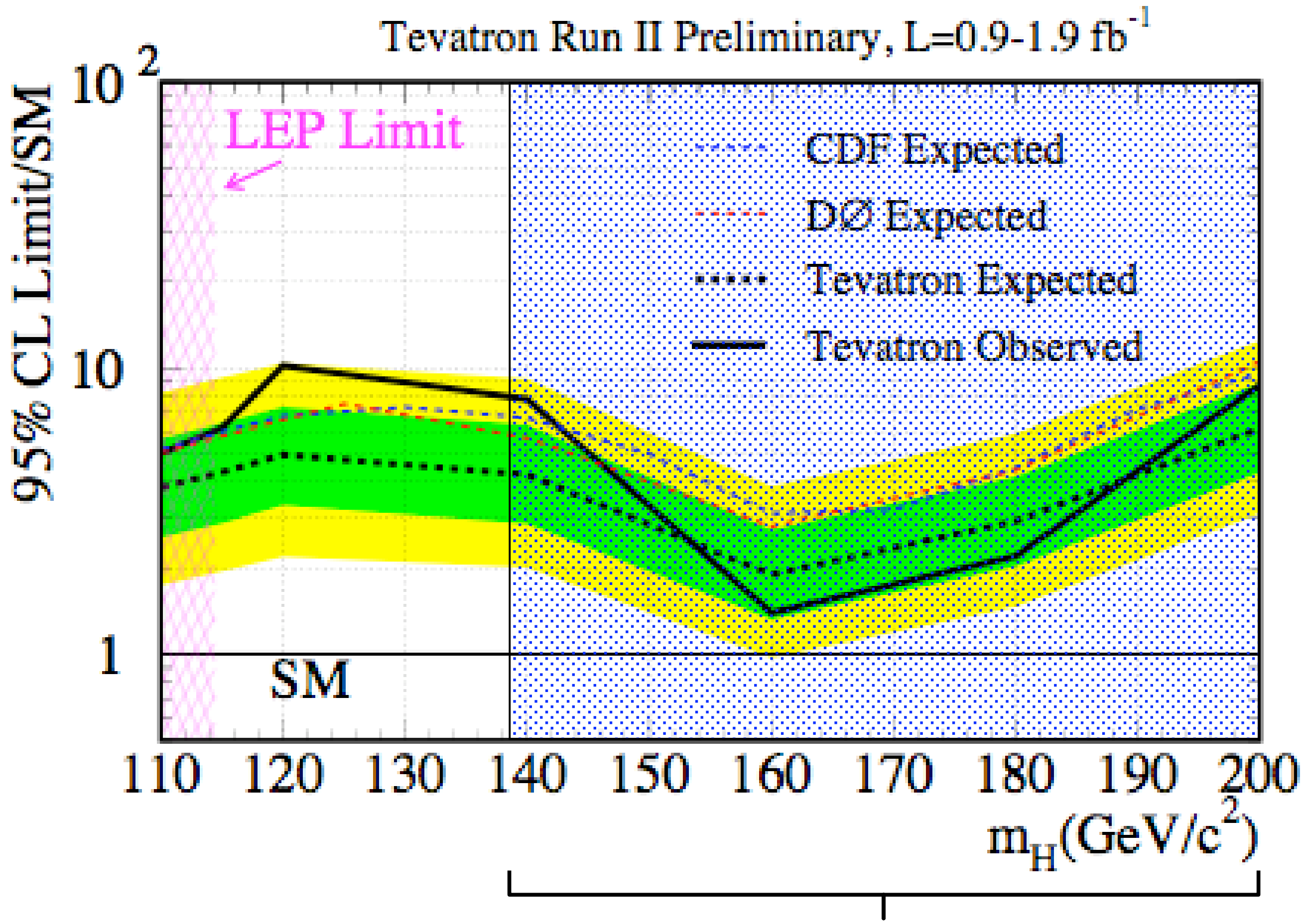
CDF: 0.2/fb

Updates

coming soon!



Combination



Very close to SM prediction

Expect: *1.9*

Observe: *1.4*

Very exciting time

No evidence for Higgs

High mass sensitivity

approaching SM

Sensitivity improving rapidly

faster than √L

More improvements coming

Vector boson fusion

More lepton acceptance

Much more to say

before LHC turns on!